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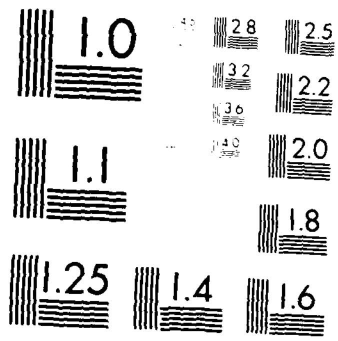

MICROCOPY RESOLUTION TEST CHART

TECHNICAL REPORT RR-83-1

URBAN INFLUENCES ON FOG

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Research Directorate
US Army Missile Laboratory

December 1982

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35809

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1. REPORT NUMBER [illegible]	2. GOVT ACCESSION NO. 3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Urban Influences on Fog	5. TYPE OF REPORT & PERIOD COVERED
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Dr. Dorathy A. Stewart	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Commander US Army Missile Command ATTN: DRSMI-[illegible] Redstone Arsenal, AL 35898	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Commander US Army Missile Command ATTN: DRSMI-RPT Redstone Arsenal, AL 35898	12. REPORT DATE December 1982
	13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

anthropogenic
urban heat
meteorological

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the [illegible] work on the [illegible] Laboratory Independent research project "[illegible] Secular Trends in [illegible]." The first step was to make a [illegible] literature survey of what is presently known about anthropogenic [illegible] atmospheric trends. This survey revealed that there is no general agreement concerning some basic questions, i.e., in which [illegible] the urban heat island is strongest.

Water vapor in fog was investigated. [illegible] fluctuations in

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meteorological conditions at three German stations masked any trend in mean dew point in fog which otherwise might have occurred during a period in which the number of automobiles increased more than 10 times. This effect was partially eliminated by comparing hours when the atmosphere is very stable with less stable hours during which anthropogenically produced water vapor is likely to be diluted by mixture through a deep layer. Berlin and Frankfurt showed a trend in winter in which dew points during stable hours increased relative to those during less stable times. Dew points during fog in winter and spring at Frankfurt also increased with time relative to dew points during fog at two nearby small towns.

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ACKNOWLEDGMENTS

The author appreciates the encouragement and helpful advice of Dr. Oskar M. Essenwanger. She also acknowledges Mr. Helmut P. Dudel for use of a German statistical yearbook and detailed maps of land use throughout West Germany. Personnel at Redstone Scientific Information Center deserve credit for maintaining an excellent library from which very old and obscure references can be obtained. Finally, thanks go to Mrs. Mona L. White for her very careful typing of the manuscript.

I. INTRODUCTION

Atmospheric visibility is strongly influenced by anthropogenic effects, and many of these effects are subject to rapid change in emergency situations which may develop during wartime. Such emergencies can last a long time during armed conflict. Furthermore, certain critical developments such as the interruption of fuel supplies can occur even in the absence of open hostilities. An example of this kind of problem was the embargo of oil by Arab suppliers to the United States a few years ago. In the future, the Soviets may stop supplying natural gas to Western Europe. According to Marshall (1981a,b) many observers estimate that the West German use of Soviet gas will reach values up to 30 percent by the end of the century, and a few people even suggest figures as high as 40 percent. It is believed that in some areas 50 percent of the houses will use Soviet gas. This report is concerned with anthropogenic effects which would be influenced by developments of this kind which accompany war but do not depend upon being near a battlefield.

This publication describes work which was done during the first year on an in-house laboratory independent research project. "Factors Affecting Atmospheric Secular Trends in Wartime." The main subject is fog. Section II contains background material on meteorological parameters which influence visibility, and Section III discusses how human activities affect these parameters. Section IV relates the results of a study of long term trends in the water vapor content of fog in large German cities. Section V consists of a summary and a discussion of conclusions.

II. METEOROLOGICAL CONDITIONS AFFECTING VISIBILITY

According to standard weather observing practice in the United States, daytime visibility is defined as the greatest distance in a given direction at which it is just possible for an observer with normal eyesight to see and identify with the unaided eye a prominent dark object against the sky at the horizon. At night, a known, preferably unfocused, moderately intense light source is substituted for the dark object (Huschke, 1959). For practical purposes, this may be considered to be a subjective estimate of the meteorological range, V, which is defined according to the formula

$$V = \frac{1}{\sigma} \ln \frac{1}{\varepsilon} \tag{1}$$

where σ is the extinction coefficient and ε is the threshold of brightness contrast. A standard value of ε is 0,02, which has been chosen to agree with empirical measurements. The extinction coefficient depends upon the number and size of particles in the atmosphere. Further discussion may be found in Johnson (1954) or McCartney (1976).

If the particles in the atmosphere are spherical and have radii less than about one-tenth the wavelength of scattered energy, Rayleigh scattering is said to occur. According to Rayleigh's law, the scattering coefficient is inversely proportional to the fourth power of the wavelength and directly proportional to the number of scatterers and the sixth power of the radius (Huschke, 1959). Scattering by molecules of atmospheric gases is usually assumed to follow the Rayleigh law. Rayleigh scattering optical depths are accurate to within 4 percent according to Hoyt (1977), or 1 percent according

to Young (1981). Young (1982) discusses Rayleigh scattering in detail in a survey article. The Rayleigh approximation is useful only in very clear air.

Extinction of electromagentic energy by larger spherical particles with a known complex index of refraction depends upon both scattering and absorption in a complicated way described by Mie (1908). Modern explanations of this electromagnetic propagation theory can be found in Kerker (1969), McCartney (1976), Deirmendjian et al. (1961), Weeks (1964), Stephens et al. (1971), and Verner (1976).

Most air contains many particles which are much larger than gas molecules. One source of submicron particles is gas-to-particle conversion. Automabile exhaust also produces large numbers of very small particles. Sea salt nuclei have radii which vary from a fraction of a micrometer to serveral micrometers (Mason, 1971). Particles in pollution from industrial sources have an even larger range of sizes than sea salt. Radii of soil particles are generally greater than 1 μm (Friedlander, 1977, p. 307.). Johnson (1976, 1982) has summarized the results of recent aerosol measurements which indicate that particles from 10 to 100 μm exist regularly in the atmosphere. Most of these ultragiant particles are mixtures of soluble and insoluble materials, but the insoluble components normally predominate.

The average size of particles in the atmospehre is influenced by the relative humidity because so many of the particles are hygroscopic, and even particles which are not hygroscopic may be moderately effective as condensation nuclei (Huschke, 1959). Condensation on hygroscopic nuclei may begin at relative humidities much lower than 100 percent. For example, condensation on sodium chloride may begin at a relative humidity as low as 75 percent. Orr et al. (1958) found that many nuclei with radii less than 1 μm have solubilities greater than normal and thus form droplets at relative humidities lower than that over a saturated bulk solution. The smaller a particle is, the lower relative humidity at which it goes into solution. The conditions under which solution and crystallization occur also depend upon the characteristics of the material, but a drop which is subjected to decreasing humidities recrystallizes at a lower humidity than the humidity at which it became a drop. Hänel's (1976) survey article summarizes much of the earlier work on the properties of atmospheric particles as a function of relative humidity. More recent discussions of the condensation activities of various aerosols may be found in Bullrich and Hänel (1978), Thudium (1978), Hung et al. (1979), and Winkler et al. (1981). The chemistry of aqueous atmospheric aerosols has been throughly reviewed by Graedel and Weschler (1981). Moisture is of practical interest because there is evidence that visibility in the atmosphere is related to humidity (Deacon, 1969; Daoo et al. (1982), and propagation at other wavelengths depends upon absolute humidity.

The water content of the atmosphere varies greatly from place to place. Cold, dry air contains less than a small fraction of a percent water vapor, but warm, moist air may contain approximately 4 percent water vapor. These large fluctuations depend not only upon variations in relative humidity, but also upon the fact that saturation vapor pressure depends very strongly upon temperature (Murray, 1967; List, 1958; and Buck, 1981). In fact, the increase of saturation vapor pressure with temperature is exponential to a crude first approximation.

Both absolute and relative humidities normally have a significant mean diurnal variation in any given location (Godske et al., 1957; Oke, 1978). The change is especially large in continental areas in summer in midlatitudes where a double cycle is typical. A minimum of water vapor coincides with the temperature minimum in the early morning hours. After sunrise, evaporation of dew or other moisture from the surface causes an increase in water vapor, and a profile develops in which absolute humidity decreases rapidly with altitude. The increase of turbulence in the afternoon causes water vapor near the surface to be mixed through a deeper layer, and a secondary minimum occures. This secondary minimum is most pronounced in dry climates. In late afternoon evaporation continues and vertical mixing decreases. By early evening the amount of water vapor reaches another maximum. During the night there is a decrease of moisture. Radiative cooling of the surface at night may cause a large enough downward flux of moisture to produce dewfall. If there is sufficient dewfall, a moisture inversion may develop. Over large bodies of water the variation of vapor pressure is approximately parallel to the temperature variation. However, in maritime locations the overall diurnal variation in water vapor is small, and the temperature variation is sufficiently large that relative humidity changes are opposite to temperature changes.

The effect of stability on relative humidity at a location in Germany was studied by Havlik (1970). Freiburg at 259m was compared with the nearby station Feldberg at 1486m. During the months September through March the average relative humidity was 79 percent at Freiburg and 84 percent at Feldberg. The averages for days with all day temperature inversions during these months were 90 percent for Freiburg and 43 percent for Feldberg. Havlik's study indicates that a large portion of the difference in relative humidity was due to difference in temperature.

More recently, Klug and Webs (1981) examined vertical distribution of specific humidity in the lowest 300m of the atmosphere. Information from 1241 soundings taken irregularly over a four-year period in various regions of the Federal Republic of Germany was used to compare humidity profiles with thermal stability and with time of day. Under very stable conditions 27 percent of the profiles showed an increase of at least 0.5g of water vapor per kg of moist air between the surface and 100m, but under very unstable conditions not one humidity inversion was that strong. Intermediate percentages occurred with intermediate stabilities. Humidity increases of 0.5g/kg or more between the surface and 100m occurred 16 percent of the time at night, 10 percent in the morning, 5 percent during the day, and 6 percent in the evening. The average overall was 9 percent. The diurnal variation was similar between 100 and 200m, but only a little more than 5 percent of the soundings had increases of specific humidity as great at 0.5g/kg between these two levels. These marked humidity inversions occurred only 4 percent of the time between 200 and 300m.

If meteorological conditions are such that the atmosphere is saturated, then a reduction in temperature or an addition of water vapor will cause condensation to occur. Air in a laboratory can be cleaned to permit relative humidities of a few hundred percent, but available evidence indicates that supersaturations remain below 1 percent in the real atmosphere (Johnson, [illegible]; Low, 1975; and Gerber, 1981). When condensation near the surface of the earth produces an aggregate of very small water drops, the result is called fog if

horizontal visibility is one kilometer or less and mist if visibility is greater than one kilometer, according to the Glossary of Meteorology (Huschke, 1959). Some investigators use the term thin fog instead of mist for visibilities between 1 and 2 kilometers (McCartney, 1976, see p. 43). In some practical applications such as aviation, fog is considered to exist for visibilities less than or equal to six miles (9.66 km). Definitions from the Glossary of Meteorology will be used in this report. Mist is intermediate between fog and haze. Haze consists of dry or damp particles which are so small that they cannot be felt or seen individually by the human eye.

Considerable information about fog has been summarized by Stewart and Essenwanger (1982). Fogs which form primarily as the result of radiational cooling of the surface at night are called radiation fogs. There is considerable variation among radiation fogs, and fluctuations may be large within a single radiation fog (Chisholm and Kruse, 1974; Smith, 1978; and Gerber, 1981). Nevertheless, on the average they have smaller drops than other fogs. Advection fog is fog which forms when warm, moist air moves over a surface which has a lower temperature. Frontal fog may be caused by rain falling into cooler air or by mixing of different air masses near a frontal zone. When cold air moves over a warmer body of water, steam fog may form. An up-slope fog is formed when air flows upward over rising terrain and cools adiabatically below the dew point.

Stewart and Essenwanger (1982) classified fog as radiation or nonradiation fog on the basis of objective criteria suitable for computerized analysis of large data collections. A clear or partly cloudly sky associated with a significant decrease in temperature produces radiation fog. Precipitation or an overcast sky implies the presence of predominantly nonradiative processes. The model was applied to data from 10 German stations.

A representative sample of drop-size distributions was chosen from the literature for radiation and nonradiation fogs, and average ratios of droplet attenuation at 10.6, 870 and 1250 μm to attenuation at 0.55 μm were obtained for each type of fog. It was concluded that the relative attenuations of visible wavelengths and wavelengths near 10 μm depend crucially upon the shape of the drop-size distribution. Attenuation of wavelengths near one millimeter by fog droplets is always less than attenuation of the much shorter wavelengths. However, attenuation by water vapor is significant near one millimeter even in window regions between strong absorption lines. Attenuation of liquid plus water vapor is smaller for 1250 μm than for 870 μm or 10.6 μm in fogs of different visibilities in all seasons in Germany. When visibilities are less than 400 m, 10.6 μm is attenuated more than 870 μm in all seasons. In spring, summer, and fall attenuations of 10.6 and 870 μm in moderate fogs are the same order of magnitude.

III. ANTHROPOGENIC EFFECTS ON VISIBILITY

There is some evidence that average visibilities are lower in a city than in the surrounding countryside. Landsberg (1981) states that visibilities less than 10 km are 5-15 percent more common in urban environments than in rural areas. Fog is twice as common in metropolitan areas as in the surrounding agricultural environment in winter and 30 percent more common in summer, according to Landsberg (1981).

However, one should not asssume that cities always have lower visibilities than their surroundings (Changnon et al., 1971). Landsberg (1981) himself pointed out that it is not uncommon to have fog in the country and only very low stratus over the airport nearest the city. Furthermore, the heaviest fogs are frequently found in the suburbs in a ring around a city (Chandler, 1976). Often, fog first forms in a ring near the edge of a city because its center has a higher temperature and a lower relative humidity. Collier (1970) compared fog statistics from Manchester Weather Centre near the center of Manchester, England, with statistics from Ringway Airport approximately nine miles south of the center of the city. There were fewer than half as many foggy days (visibility < 1 km) at the airport, but dense fogs with visibilities less than 500 m occurred slightly more frequently at the airport.

Combustion of fuel produces water vapor. This can be especially significant in the production of fog at higher latitudes because of the lower temperatures. For example, air at 20°C can hold approximately 100 times as much water vapor as air at -40°C.

Ice fogs at Fairbanks, Alaska, illustrate the effects of water vapor pollution when temperatures are very low. Bowling et al. (1968) examined 15 periods of dense fog at Fairbanks. Their detailed study showed that 12 of 15 cases followed a similar pattern in which the main phase was associated with surface temperature inversions, and the surface temperatures were -40°C or lower. These stable conditions prevent vertical mixing of the water vapor, and vertical thicknesses of ice fog in Fairbanks are typically 10 m and seldom reach more than 30 m (Benson, 1970). Human activities which produce water vapor in Fairbanks are cooling water from power plants and combustion of gasoline, fuel oil, and coal. Only 3 percent comes from automobile exhaust, but it is still important because the input is so near the surface and is where the people are.

Anthropogenic sources of water vapor also have an effect on visibility in Edmonton, Alberta. Robertson (1955) examined data from the Edmonton Municipal Airport for the 1949-50 winter. A few simplifying assumptions were made in order to estimate the time required for air to become saturated as a result of combustion of natural gas. When low temperatures and moderate natural humidities occur, combustion can produce enough water to saturate the air in an hour or less in calm air. Hage (1972) compared the results of Robertson's (1955) study with data from the 1968-69 winter at Edmonton. The population increased from 159,000 in 1950 to 410,000 in 1969, and the area of gas consumption increased from 46 km^2 to 170 km^2. Hage concluded that the total production of water vapor in the metropolitan area on a cold day was seven times as large in the 1968-69 winter than in the 1949-50 winter. The principal sources of water vapor were the combustion of natural gas and

evaporation from cooling towers. About 2.5 percent resulted from combustion of motor vehicle fuel. Dense fog on cold winter days occurred at temperatures 5°C higher in the 1968–69 winter than in the 1949–50 winter.

Hage (1975) examined urban-rural humidity differences throughout the year at Edmonton during a 13-year period for which simultaneous observations were available at an airport within the city and at Edmonton International Airport 26 km south of the center of the city. Average relative humidities were lower in the city except in winter. In summer at night mean monthly relative humidities were more than 10 percent lower in the city than in the country. On the other hand, absolute humidities at night were higher in the city throughout the year. During the day urban absolute humidities were greater than rural absolute humidities in colder months and smaller in warmer months. Hage showed that the greater urban absolute humidity depended not only upon combustion but also upon vertical mixing. Measurements from a nearby rural radiosonde station revealed that average mixing ratios increased with height in the lowest several hundred meters at night during the winter. Urban air is less stable because of the heat island, and Hage made computations which indicated that vertical mixing contributed 20 percent or more to the excess urban water vapor at night in winter. Another factor which sometimes contributes to increased moisture content over a city is melting snow. Hage's data from Edmonton for March 1966-73 at 0500 hours local time illustrate this point. Absolute humidities are sometimes 1 g/m^3 larger in the city when snow is on the ground and temperatures are near 0°C. However, when snow persists in rural areas after it has melted in urban areas the effect is smaller.

Several other studies have contradicted the long-held belief that cities are usually drier than their surroundings. Chandler's (1967) measurements in the summer of 1966 in Leicester, England, showed that nocturnal absolute humidities were generally higher in the city than in the surrounding environment. Chandler's explanation was that in the cooler rural areas a flux of water vapor to the surface caused dew to form. Dewfall was also offered as an explanation to account for lower dew points at night throughout the year in rural areas around Chicago (Oke, 1974, pp. 59-60). The Chicago study showed that in winter the city was more humid than the countryside throughout the 24-hour day. The greater absolute humidity in the countryside in the summer during the day was attributed to greater evapotranspiration in the rural environment. According to Garstang et el. (1975), a strong mixing ratio maximum has been observed over Johannesburg in winter at the time of minimum temperature on nights with inversions, and there is even a weak maximum in the middle of the day in summer. Garstang also discussed a study in New York which showed that a moisture excess of approximately 4 percent extended to heights of 500-700 m at night. Nocturnal and early morning maxima of absolute humidity also occur often over St. Louis, Missouri, but during the afternoon in the summer urban deficits may be larger than 2 g/m^3 (Dirks, 1974a,b; Sisterson and Dirks, 1978). Even the Chapel Hill and Carrboro urban area of approximately 29,000 people in North Carolina showed distinct nocturnal maxima and daytime minima of water vapor (Kopec, 1973).

A very long-term study by Landsberg (1951) compared the period 1891-1920 with the period 1921-1950 at Washington, D.C. Average dew points were higher in the later period during November, December, January and February, and the differences were large enough in November and February to represent about 0.3g/m^3. During April through October dew points were about the same during

the two 30-year periods, and during March the mean dew point was lower during the later period. Mean relative humidities were smaller and mean temperatures were greater during the later period in all months.

Localized activity also affects the nature and probability of occurrence of fog. Cong and Dessens (1973) measured drop sizes in fogs along the upper Garonne River in a valley. Two fogs were localized near a pulp mill which ejected large amounts of water vapor into the atmosphere and two were spread throughout the valley basin. Mean droplet radii were nearly twice as large in the localized fog. Cooling lakes for nuclear power plants can also cause initiation or enhancement of fog. Vogel and Huff (1974, 1975) made some theoretical computations based upon earlier measurements in the midwestern part of the United States, and they concluded that the effects of cooling lakes are greatest in winter. Very small-scale human activity is also sometimes important. Gillett (1954) of the British Meteorological Office at Stornoway Airport described a situation in which an airplane stirred up particles of snow in a swirling cloud to a height of approximately 15 m and shallow fog subsequently formed. The fog soon covered the entire airfield and lasted more than an hour.

Although the absolute humidity quite frequently has a maximum over an urban area, the relative humidity is usually lower because air temperatures tend to be higher in a metropolitan area than in the surrounding region. The warmer area is known as the urban heat island. There is no general agreement concerning when the heat island effect is greatest. Changnon et al. (1971) and Kopec (1973) indicated that the urban heat island is strongest at night and in the winter. Sanderson et al. (1973) found maximum urban-rural temperature differences in the early morning hours and during the months August through October for Detroit, Michigan. Oke (1982) concluded that the most intense heat islands typically occur during the warmer half of the year in temperature latitudes. In any case, Matson et al. (1978) detected more than 50 urban heat islands on thermal infrared images of the midwestern and northeastern United States from the NOAA5 satellite. Their analysis of digital data for a very clear night in July revealed maximum urban-rural temperature differences ranging from 2.6 to 6.5°C. Garstang et al. (1975) pointed out that urban heat islands may be as much as 20°C hotter than their surroundings.

The difference between urban and rural temperatures is also a function of meteorological variables. Sundborg (1950) examined data from Uppsala and concluded that the urban minus rural temperature difference decreased linearly as cloudiness, wind speed, and temperature increased, regardless of the time of day. Sundborg's data indicated that during the day the temperature contrast becomes smaller as the absolute humidity becomes larger, but at night larger absolute humidities are associated with larger temperature differences. Munn (1973) suggested that the urban minus rural temperature difference varied directly as the square root of the rural vertical gradient of potential temperature and inversely as the square root of a representative rural wind speed. Munn found that this relationship was compatible with data from the Toronto area. Ahrens (1981) postulated that urban-rural temperature contrast was linearly related to the vertical temperature gradient and found that this agreed fairly well with data from several locations. According to Ahrens, the city is warmer than the rural environment during stable conditions and colder when the atmosphere has an unstable

stratification. Oke's (1982) survey article about the heat island also pointed out that a city may sometimes be cooler than its surroundings.

Anthropogenic heat release is one obvious cause of the urban heat island, but there are other contributing factors (Oke, 1978). Many construction materials have greater heat storage capacity than rural surfaces. Furthermore, where there are tall buildings, the radiation heat loss is less and lower wind speeds are associated with decreased heat loss. There may also be decreased evapotranspiration from construction materials compared to agricultural areas.

However, urban material does absorb water. Chandler (1976) points out that the amount of moisture absorbed by brick and tile has frequently been underestimated. Oke (1974) also suggests that building materials absorb appreciable quantities of water and quotes evidence from a study in which the recorded runoff during rain in a part of London which was 95 percent paved was only half the measured rainfall. Reidat (1981) claims that the moisture content of concrete varies from 3.0 to 17.0 percent by volume.

Of course, an urban area is not uniform and does not consist entirely of materials such as asphalt and concrete. Marotz and Coiner (1973) carefully examined the surface area of five cities in Kansas. They defined natural surfaces to include grass, bushes, trees, bare soil, rock, water, and sand. More than half the area in each of the five cities consisted of a natural surface. Auer (1978) examined photographs from aerial reconnaissance of the greater St. Louis area. More than half a million people live within the city limits, and over two million people live within the St. Louis metropolitan area. There is approximately 45 percent vegetative cover within the city limits and an estimated 65 percent within the St. Louis metropolitan area. Akhmedzhanov and Degtyarov (1979) discussed the microclimate of Alma-Ata in Soviet Central Asia. In one set of measurements the maximum air temperature on Lenin Square was 2.3°C higher than in an adjacent garden, and the relative humidity was 14 percent lower. It was also found that fountains increase the relative humidity by 10-20 percent and lower the temperature 1-3°C.

An interesting example of the effects of the underlying surface in causing moisture to be deposited from the atmosphere was discussed by Davey (1982). On 10 December 1980, some unusual condensation occurred on road surfaces near Lyneham, England. By late evening enough moisture to form pools had collected on the roads, even though rain gages, exposed metal and glass objects, and grass showed no evidence of precipitation or condensation off the roads. Forecasters have known for a long time that such condensation can occur when there is a sudden change from cold to much milder weather. The event described by Davey is unusual because it happened long after the onset of milder weather. Furthermore, Davey's record of temperatures 5 mm below the surface of a concrete slab contained no values more than 0.7°C lower than the simultaneous dew point at the standard shelter.

It is obvious from the above discussions that determining the effects of human behavior on the atmosphere is not easy. Different investigators do not even agree in which part of the year the urban heat island is strongest in middle latitudes. Both the geometry of the urban environment and anthropogenic heat sources appear to be important in producing the urban heat island. The influence of combustion is greater in winter and at higher latitudes.

Combustion also produces water vapor, and this is much more significant in winter because of the lower saturation vapor pressures at lower temperatures. The next section of this report considers the variations of water vapor during fog in large German cities over a 24-year period.

IV. WATER VAPOR IN GERMAN FOG

Because of increased combustion associated with automobiles, airplanes, and industry, it is reasonable to expect that the water vapor content of fogs in and near large cities has increased during the past few decades. For example, fog formed at temperatures 5°C higher during the 1968-69 winter than during the 1949-50 winter in Edmonton, Alberta. Hage (1972) attributed this to a seven-fold increase in the amount of water vapor released into the atmosphere by combustion of natural gas and motor vehicle fuel. Unfortunately, most statistical tabulations of meteorological data are not broken down into categories so that one can determine temperature or dew point during fog. In the present study, German data from Berlin, Frankfurt, and Stuttgart were examined.

Fog is defined as visibility less than or equal to one kilometer, but one kilometer is not one of the coded values on the TDF14 tapes which were used. Therefore, the analysis of fog considered all values of visibility less than or equal to one-half mile (0.805 km) because the next higher code number represents five-eighths mile (1.006 km). Hourly observations were available during most of the period of record, and three-hourly intervals were used the remaining part of the record.

The amount of water vapor in the atmosphere depends primarily upon the dew point and slightly upon the temperature. Because the temperature and dew point are always within a few degrees of each other in fog, the amount of water vapor in fog is essentially a function of dew point only. Therefore, it was decided to analyze variations of the dew point in fog over the years. Water vapor from human activities was expected to be most important in winter because of the lower saturation vapor pressures which are associated with lower temperatures.

Observations of mean dew point during fog from the winters 1946-47 through 1969-70 at Berlin, Frankfurt, and Stuttgart failed to show the expected trend even though the number of automobiles in Germany increased approximately 25 times from 1950 to 1970 (Statistisches Bundesamt, 1977). Year-to-year fluctuations were so large that any underlying trend in the data was masked (see Figure 1, Berlin). Furthermore, trends during fall at the three stations were no better, and good trends were also absent in spring. Little fog occurs in summer.

It was necessary to develop a method to remove the effect of large-scale meteorological variations from one year to the next. Consideration of weekdays and weekends separately did not produce significant new information. Division of the fogs into categories with different wind speeds did not result in an obvious trend of dew point in any category. It was finally decided to separate fogs into groups according to time of day. Even when fog is present during the day, some solar energy reaches the surface of the earth and causes slow warming. Thus, the atmosphere can be expected to be less stable

in the afternoon and early evening than in the morning hours. When the atmosphere becomes less stable, water vapor is mixed through a deeper layer.

The average of all observations of dew point during fog from 2300 through 1000 hours GMT was subtracted from the average of observations during 1100-2200 GMT for each season of each year. This difference should decrease with time as the anthropogenic input of water vapor increases because the vapor increase should be trapped near the surface during the stable late night and morning hours. The variation of the difference between average dew points during fogs which occurred at different times of day during winter at Berlin is shown in Figure 2. Rather large fluctuations exist, but there is definitely a trend toward lower values in the later years. Figure 3 illustrates that a moderately good trend occurred in winter at Frankfurt, but evidence for a trend is poor at Stuttgart (Figure 4). Trends were better in winter than in fall at all three stations. There was not enough afternoon and evening fog in spring and summer to do the analysis. Observations from Berlin probably show the best trend of the three stations because the measuring site is the most urban, and West Berlin alone has a population of more than two million. Measurements for Stuttgart are far from the urban center, and the city itself has a great many parks. The observations for Frankfurt are at the airport, which is a few kilometers south of the edge of the built-up area and is at the intersection of two main highways. The Frankfurt airport is approximately 25 km east of Wiesbaden.

Another method which can potentially isolate urban influences and eliminate the effects of large-scale meteorological fluctuations is to compare observations from large cities with those from small towns. Hahn is approximately 100 km west of Frankfurt. Bitburg is nearly 150 km west of Frankfurt.

Figure 5 is a graph of the result of subtracting the average dew point during fog at Hahn from the average dew point during fog at Frankfurt for 17 winters. There appears to be an overall trend toward higher values during the later years, but some rather large fluctuations occur from year to year. A similar trend was found for the difference between Frankfurt and Bitburg.

The minimum dew point which occurred during fog each winter at Hahn was subtracted from the minimum for the same winter at Frankfurt to obtain Figure 6. After the 1957-58 winter, all differences are positive except for one slightly negative value during the 1963-64 winter, and there is a very good trend in the data. The minimums at Frankfurt during the winter also increased relative to those at Bitburg over the years.

The most surprising aspect of the comparison between Frankfurt and each of the two small towns was the fact that the best trend of the differences in mean dew point during fog occurred in spring. This is illustrated well in Figure 7, which is the difference of mean dew point during fog between Frankfurt and Bitburg in spring. Because of the small number of hours of fog at Frankfurt in the spring, the large trend may not be entirely reliable. On the other hand, there are reasonable explanations if it is all real. Melting or sublimation of snow during spring in fog could be greater in the more urban environment. Furthermore, the amount of automobile and airplane traffic may increase in the spring over the amount during the much harsher winter weather. More study is needed on the data for spring.

V. SUMMARY AND CONCLUSIONS

The effect of human activities on the formation of fog in a large metropolitan area is not clear cut. The urban heat island tends to cause lower relative humidity, but this is often counteracted by increased water vapor which results from combustion. Furthermore, some urban pollution consists of particles which are strongly hygroscopic and begin to form drops at relative humidities well below 100 percent. Most investigators claim that the overall average amount of fog is larger in cities than in the country. It is known that combustion contributes significantly to the formation of fog at very high latitudes in the winter.

One of the primary concerns of military planners is the water vapor in fog because water vapor absorbs electromagnetic energy, and the absorption is particularly strong for submillimeter wavelengths. The amount of water vapor in fog depends primarily upon the dew point. Therefore, it was decided to examine the variations of dew point during fog at three large German cities over a 24-year period during which the number of automobiles in Germany increased more than 20 times. Large year-to-year fluctuations in meteorological conditions at Berlin, Frankfurt, and Stuttgart masked any trend which otherwise might have occurred in the overall mean dew point during fog. However, this effect was partially eliminated by comparing hours when the atmosphere is very stable with less stable hours during which anthropogenically produced water vapor is likely to be diluted by mixture through a deep portion of the atmosphere. Berlin and Frankfurt showed a trend in which the dew points during stable hours increased relative to those during less stable times over a period of 24 winters. Finally, dew points during fog at Frankfurt showed an increasing trend relative to those at the nearby small towns of Bitburg and Hahn during winter and spring for 18 years of data.

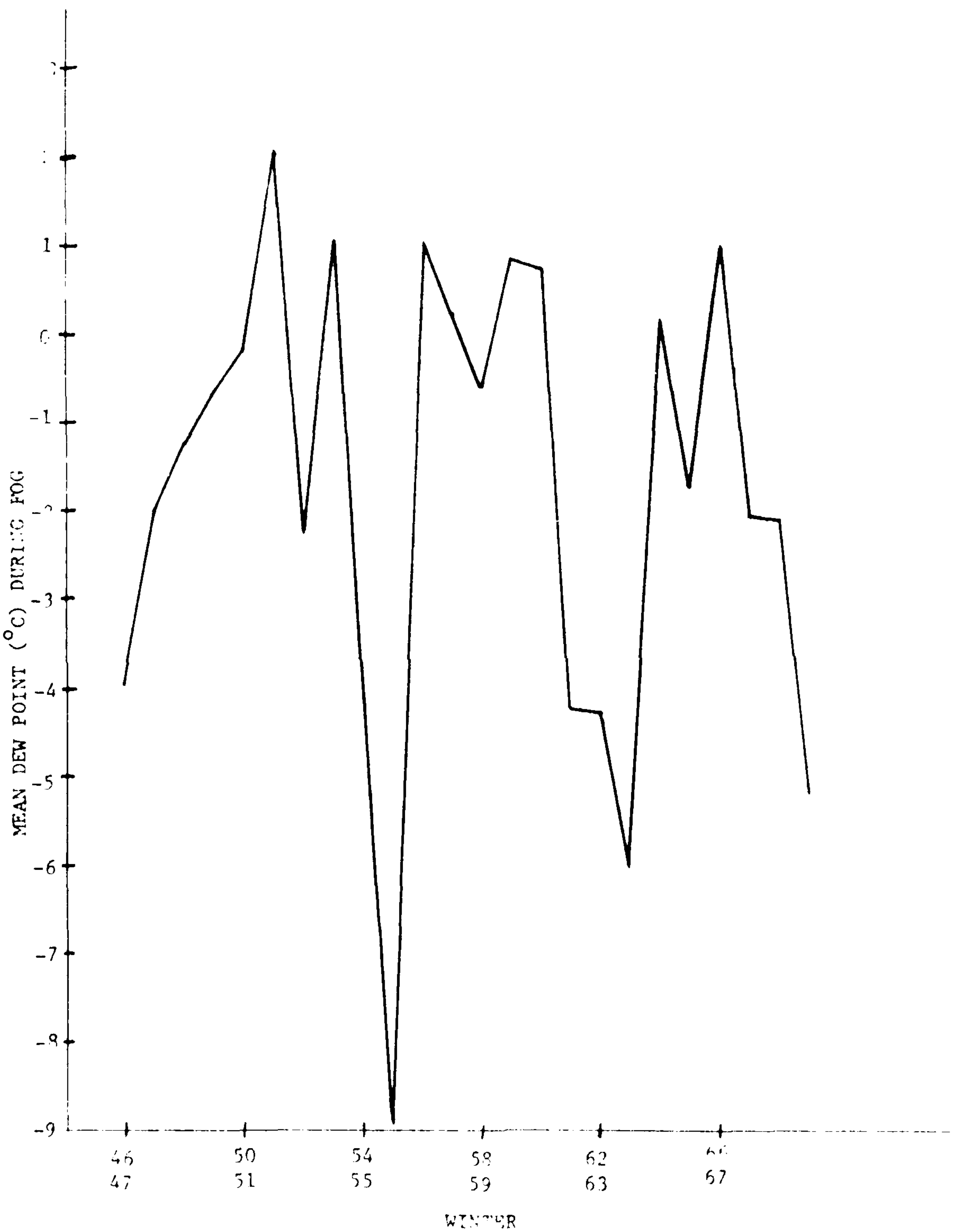

Figure 1. Mean dew points during fog in winter at Berlin.

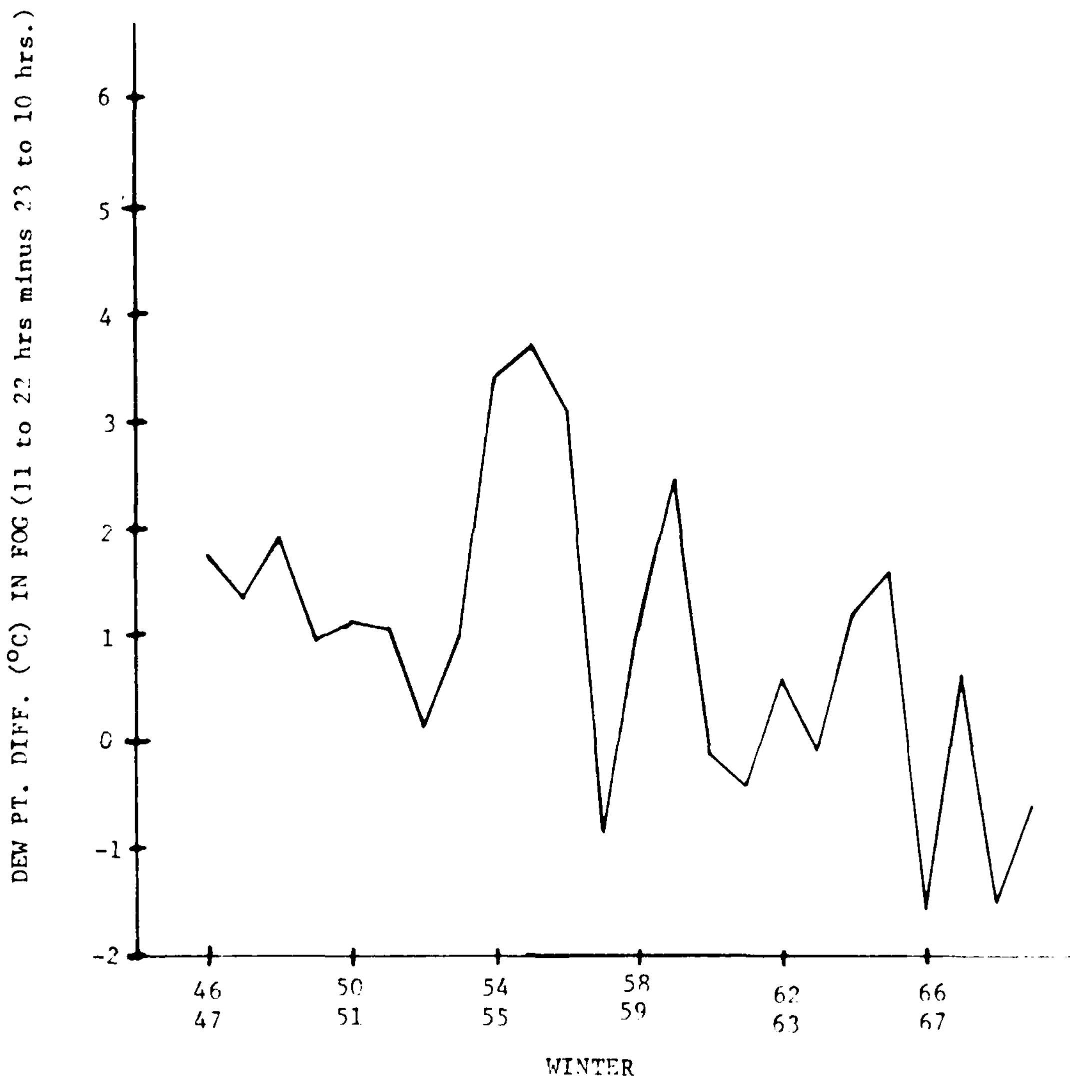

Figure 2. Dew point difference (degrees C) during fog (1100 to 2200 GMT minus 2300 to 1000 GMT) at Berlin in winter.

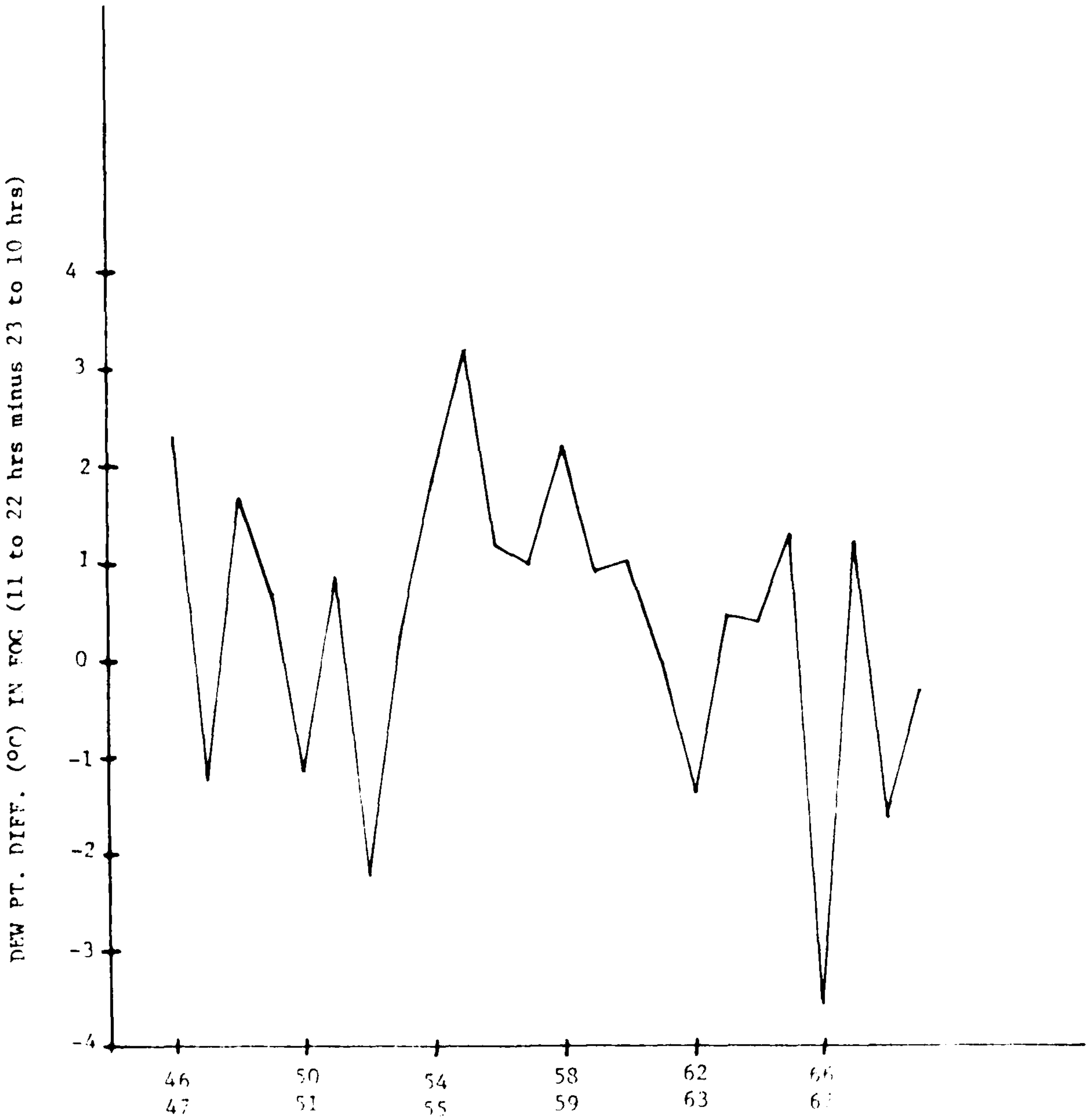

Figure [illegible]. Dew point difference (degrees C) during fog (1100 to 2200 GMT minus 2300 to 1000 GMT) at Frankfurt in winter.

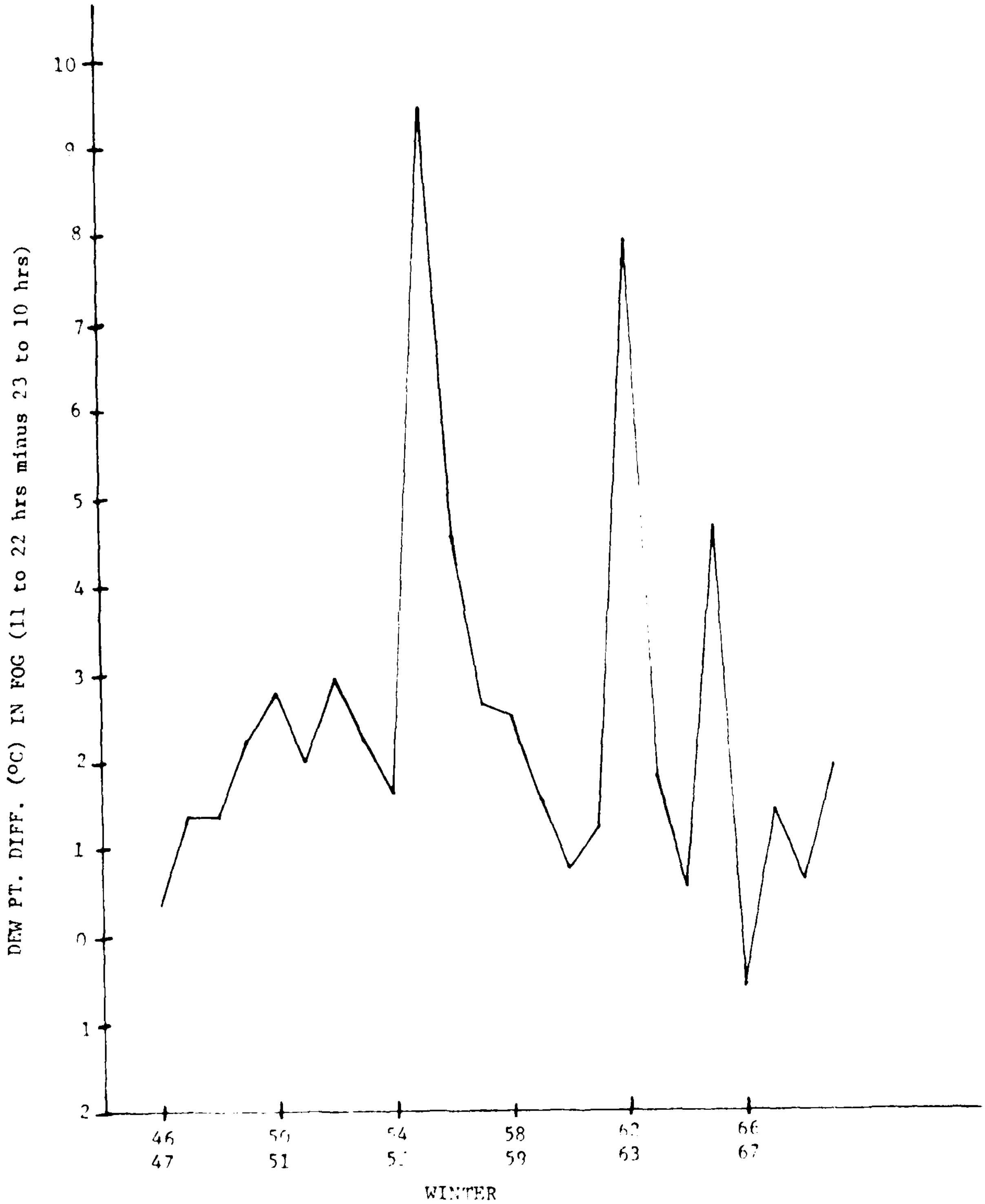

Figure 4. Dew point difference (degrees C) during fog (1100 to 2200 GMT minus 2300 to 1000 GMT) at Stuttgart in winter.

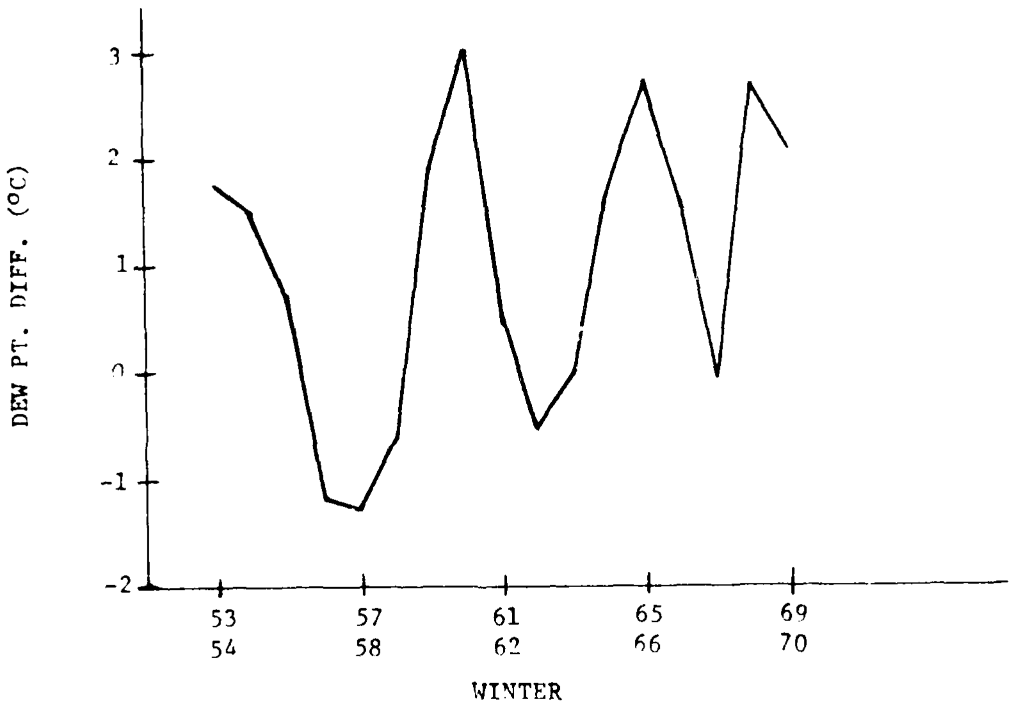

Figure 5. Difference of mean dew point during fog in winter (Frankfurt minus Hahn).

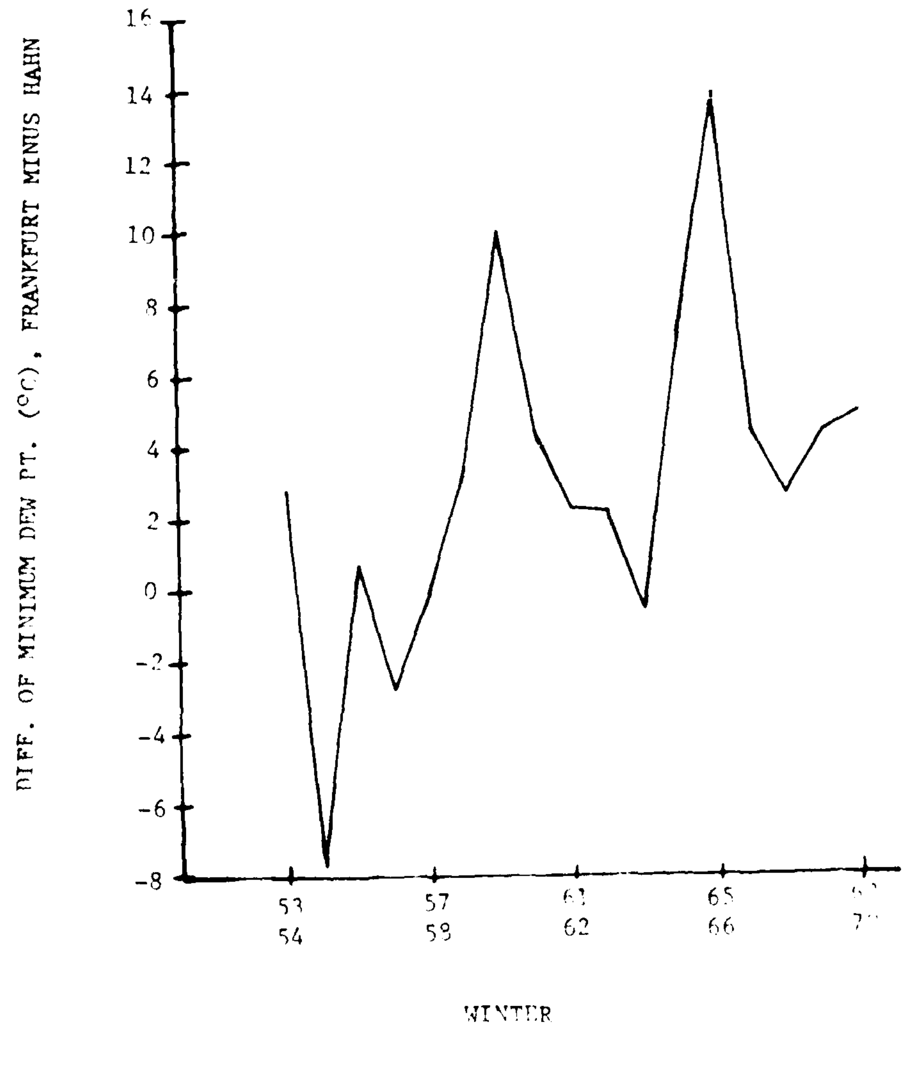

Figure 6. Difference of minimum dew point during fog in winter (Frankfurt minus Hahn).

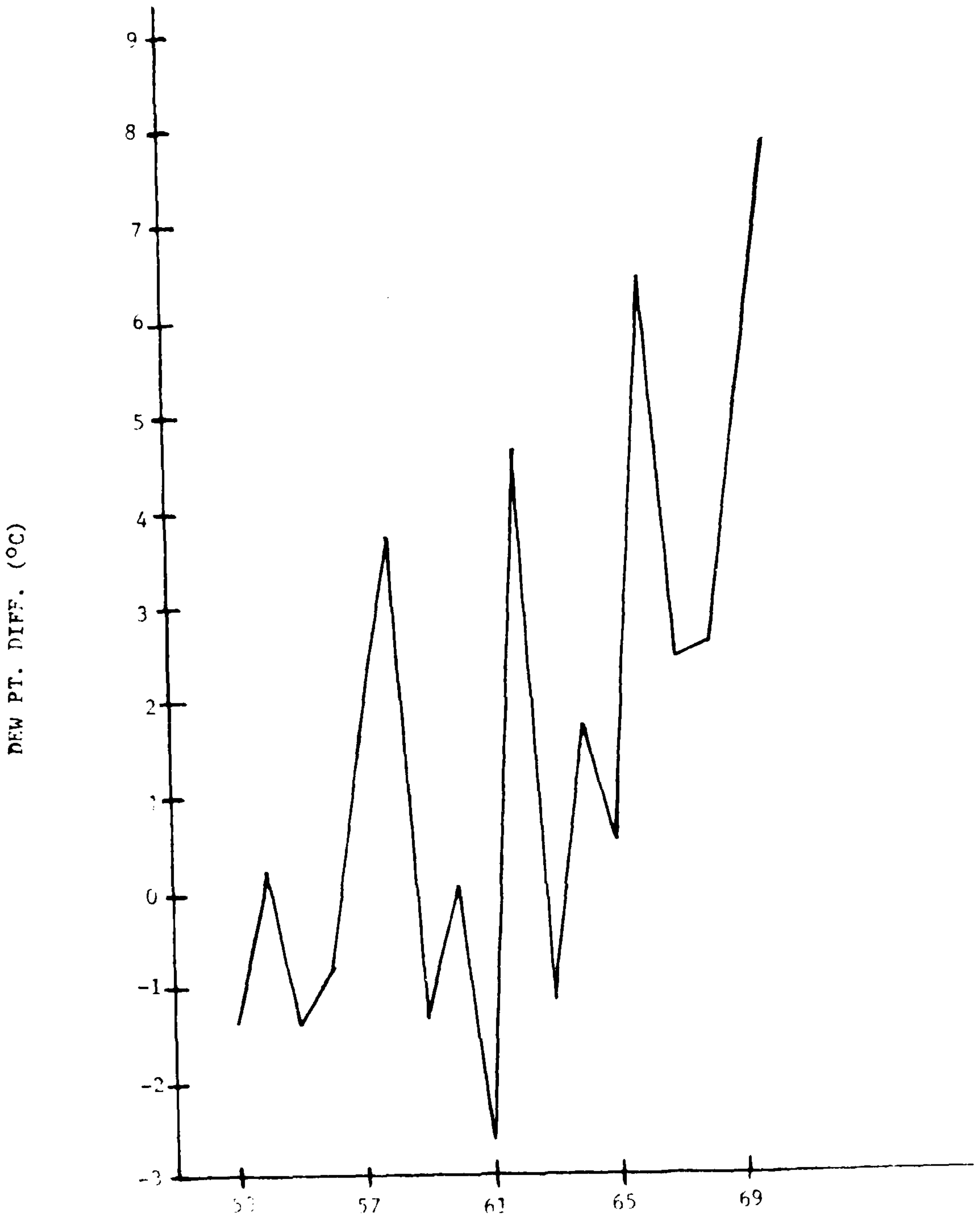

Figure 7. Difference of mean dew point during fog in spring (Frankfurt minus Bitburg).

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-RPO, Dr. Guthrie	1
-RPT (Record Copy)	1

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